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IMPACT WAVES AND DETONATION

By R. Becker

PART II

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C O N T E N T S

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PART II.

C. Applications to Detonation

8. The general fundamental equations for detonation.- It has already been stated a number of times that an insight into the microscopic processes of impulse waves is not to be expected from an analysis based on continuum concepts. Nevertheless the macroscopic characteristics of the wave may easily be deduced from (14) or (15) and (16) on the assumption that the passage of the gases through the wave front shall in no way violate the laws of the conservation of energy and of mass nor the impulse law.

To this end it is only necessary to conceive of the wave front situated between any two cross sections, I and II of the tube and apply the laws that have been deduced to this layer of gases (Fig. 7).

We will now consider the case that within the wave front lying between I and II, a chemical transformation takes place. In referring technically to such a process we will designate

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as medium 1 the initial active gases, and as medium 2 the reaction products resulting from the transformation of the active gases in their passage through the impact wave. It is easy to see that the deductions drawn from (15) and (16) are not affected by the fact that the impact wave is here bound up with a chemical transformation. This is made even more clear when we seek to determine, as in (27b) for the simple impulse wave, the energy difference $E_2 - E_1$. Evidently, the heat of reaction Q, must here be taken into account. It must here also be noted that the equation of state for medium 1 is not the same as that for medium 2. Since, however, the equation of state for the initial active components - the values of p_1, v_1, T_1 - are usually known, the corresponding values for the reaction products p_2, v_2, T_2 will be of chief concern in any practical application to be made. But as long as the density of the reaction products, on account of their high temperature, is small, and therefore followed closely Boyle's law, equations (15c) and (16) will be applicable and we may write

$$D = v_1 \sqrt{\frac{p_2 - p_1}{v_1 - v_2}} \quad \ldots \ldots \qquad (40a)$$

$$W = (v_1 - v_2) \sqrt{\frac{p_2 - p_1}{v_1 - v_2}} \qquad (40b)$$

$$E_2 - E_1 = \tfrac{1}{2} (p_1 + p_2) (v_1 - v_2) \qquad (40c)$$

$$p_2 v_2 = R T_2 \qquad (40d)$$

$$E_2 - E_1 = \overline{c_v} (T_2 - T_1) - Q \qquad (40e)$$

At very high densities of the reaction products (resulting from solid explosives) (40a, b, and c) will still hold, while (40d and e) are subject to change.

In deducing equations (40) only two different states of the substances were considered - the gaseous and the liquid. The application of these equations to solid explosives may raise some question since in this case the energy E is no longer a function of v and p. Instead it depends in some complicated way on the pressure tensor. From the standpoint of their practical application, however, such questions should not be given too much weight; for in the case of solid explosives it is entirely immaterial whether we place for p_1 the actual atmospheric pressure or the value 0. The real elastic characteristics of the solid explosives do not enter into the problem. For the reaction products, on the other hand, E_2, v_2, p_2 the assumption is made that they may be treated as either gases or liquids both for the further theoretical development and also in practice.

Equations (40) hold in general for the case that a chemical transformation at constant velocity traverses the active components under the conditions already laid down for the entire consideration here undertaken, viz., that the process is a unidimensional one so that all magnitudes may be represented on a convenient right-angled coordinate system related to x but not to y nor z. Concerning the justification of these

stipulations, the following observations are offered:

Measurements of the velocity of the detonation wave have shown that if tubes of very small diameter were used to contain the explosive, lower values were obtained than where larger tubes were used; but above a certain tube diameter the rate of propagation of the detonation wave was found to be independent of the container. For consistent results with explosive gases, tubes of diameter greater than 10 mm should be used (Dixon, l.c. 1893) and for solid explosives, 30 to 50 mm (Z. B. Kast., l.c. also Z. f. d. ges. Schiess.- u. Sprengsloffwesen, 8, 156 (1913)).

In order to make plain the meaning of equations (40) we shall make use of a p, v coordinate figure (Fig. 8). The point A corresponds to the p_1 v_1 values of the explosive substance. In general, p_1 has the value 1 atm. A curve is then drawn from the Hugoniot equation (40c) on which the point p_2 v_2 must lie. We next determine for $v_2 = v_1$ the case of adiabatic transformation at constant volume. In the case of all explosives this transformation is accompanied by an increase of pressure, leading to a point G of the H-curve above the point A. The case $p_2 = p_1$ corresponds to combustion at constant pressure. This takes place with an increase of volume corresponding to an amount of work done $- (E_2 - E_1) = - p (v_1 - v_2)$. The volume corresponding to this work is indicated by the point F.

The H-curve passing through the two points G and F gives

the values for the velocity of propagation D, of the reaction together with the flow velocity W, of the reaction products (equations (40a) and (40b)). It is to be noted here that the sign of W, by compression ($v_2 < v_1$) is positive, indicating a flow in the same direction as D. By rarefaction, on the other hand, ($v_2 > v_1$), it is negative. Let α be the angle B A p_1 then,

$$D = v_1 \sqrt{\tan \alpha}, \qquad W = (v_1 - v_2) \sqrt{\tan \alpha}.$$

But $\sqrt{\tan \alpha}$ for that portion of the H-curve between G and F is imaginary and corresponds to no actual natural process. The H-curve, therefore, consists of two independent portions corresponding to two entirely different modes of a chemical transformation which will be distinguished by the names detonation and normal burning.

From the course taken by the H-curve we can make the following qualitative statements concerning these modes of transformation:

Detonation.- (The portion of the H-curve, B D G). In the reaction zone, intense increase of pressure and concentration. Direction of flow of combustion products, positive. A high propagation velocity, D.

Burning.- (The portion of the H-curve, F K). In the reaction zone, decrease of pressure and dilatation. Direction of flow of combustion products W, negative. Relatively slow rate of propagation D.

Both these phenomena have long been known in technical practice. Their qualitative distinctive characteristics were first pointed out by the discoverers of detonation, Berthelot and Vieille, also by Mallard and le Chatelier.

9. Normal detonation.- By the above consideration there has been gained a qualitative idea of the processes under consideration. The figure might convey the impression, however, that along the part of the curve B G there could be varying velocities of detonation D. But experience has shown that under careful adjustment and measurement, the detonation velocity of a definite substance has a constant value characteristic of that substance. This value remains constant over the entire length of the tube, whether the tube be only a few centimeters in length or a hundred meters. In what follows we shall show that the theory here set forth also predicts this fact and that the detonation becomes stable only for a definite point of the H-curve. This point is the point J where the tangent from A coincides with the H-curve. To substantiate this we shall show the following statement to be true: The entropy is a minimum for the point J on the curve and a maximum for the point K. These two points being the points of contact between the H-curve and the tangents drawn to the curve from the point A.

The expression for the "steepness" of any point v_2, p_2, on either the adiabatic or H-curve is given by the equations

$$\varphi = -\left(\frac{d\ p_2}{d\ v_2}\right)_{ad}; \quad \psi = -\left(\frac{d\ p_2}{d\ v_2}\right)_H \tag{41}$$

where the indices, ad, H, indicate differentiation along an adiabatic and H-curve, respectively. From the general thermodynamic equation for entropy S, (S and E are functions of v_2 and p_2)

$$T\ d\ S = d\ E + p_2\ d\ v_2 = \left(\frac{\partial E}{\partial v_2} + p_2\right) d\ v_2 + \frac{\partial E}{\partial p_2}\ d\ p_2$$

it follows that

$$\varphi = \frac{\frac{\partial E}{\partial v_2} + p_2}{\frac{\partial E}{\partial p_2}},$$

and for the H-curve, from (40c)

$$\psi = \frac{\frac{\partial E}{\partial v_2} + p_2 - \frac{1}{2}(p_2 - p_1)}{\frac{\partial E}{\partial p_2} - \frac{1}{2}(v_1 - v_2)}.$$

In this expression p_1 and v_1 may be taken as given constant, characteristic of the explosive. From these equations, it follows

$$\varphi - \psi = \frac{1}{2}\frac{(p_2 - p_1) - (v_1 - v_2)}{\frac{\partial E}{\partial p_2} - \frac{1}{2}(v_1 - v_2)} \tag{42}$$

and

$$T\left(\frac{dS}{dv}\right)_H = \frac{\partial E}{\partial v_2} + p_2 + \frac{\partial E}{\partial p_2}\left(\frac{dp_2}{dv_2}\right)_H = \frac{\partial E}{\partial p_2}(\varphi - \psi). \tag{43}$$

In case the adiabatic and H-curve touch ($\varphi = \psi$), then, of course $\left(\frac{dS}{dv}\right)_H = 0$. Equation (42) shows that at such a point,

$\varphi = \frac{p_2 - p_1}{v_1 - v_2}$. But $\frac{p_2 - p_1}{v_1 - v_2}$ is the direction of the tangent drawn from A to the H-curve. This shows that at J and K, S has extreme values. In order to determine whether these extreme values are maximum and minimum or not, the second differential is taken at these points and the assumption made that the magnitude $\frac{\partial E}{\partial p_2} - \frac{1}{2}(v_1 - v_2)$ will always be positive. This assumption would mean that ψ is finite. From (42) and (43) it follows that the sign of $\left(\frac{d^2 S}{dv^2}\right)_H$ at the points of contact is the same as that of

$$\frac{d}{dv_2}\left[(p_2 - p_1) - \varphi\,(v_1 - v_2)\right]_H = -\psi + \varphi - \left(\frac{d\varphi}{dv_2}\right)_H (v_1 - v_2).$$

But at these points

$$\varphi = \psi \quad \text{and} \quad \left(\frac{d\varphi}{dv_2}\right)_H = \left(\frac{d\varphi}{dv_2}\right)_{ad} = -\left(\frac{d^2 p^2}{dv^2}\right)_{ad}.$$

In general, the steepness φ of the adiabatic decreases with increasing volume; as a consequence $\left(\frac{d\varphi}{dv_2}\right)_{ad}$ is negative. If we represent by $\bar{v}_2$ the volume v_2 corresponding to the volume at the point of contact, we have the simple result that the sign of $\left(\frac{d^2 S}{dv^2}\right)_H$ in $\bar{v}_2$ is equal to the sign of $(v_1 - \bar{v}_2)$. The entropy, therefore, has its minimum at J and its maximum at K as stated above.

That the adiabatic and H-curve have the same direction at a point of contact J may easily be seen from the following consideration: A line drawn from A to a point B $(p_2\ v_2)$ of

the H-curve will, in general, cut this curve in a second intersection point D (p'_2 v'_2). According to equation (40c) $E_2 - E_1$ is equal to the surface A v_1 v_2 B

and $$E'_2 - E_1 = A\ v_1\ D'\ D,$$

hence $$E_2 - E'_2 = D\ D'\ v_2\ B = \tfrac{1}{2}\ (p_2 + p'_2)\ (v'_2 - v_2) \quad (44a)$$

The integral of the line D B gives its direction

$$\int_D^B T\ d\ S = \int_D^B d\ E + \int_D^B p\ d\ v$$

$$= E_2 - E'_2 - \text{surface}\ D\ D'\ v_2\ B,$$

hence $$\int_D^B T\ d\ S = 0 \quad (44)$$

When the points D and B lie together dS = 0, which is the case for the point of contact of a tangent drawn from A to the H-curve.

From equation (44) an important deduction may be drawn relative to the line D B. If the change in the integrals $\int_D^B T\ d\ S$ taken along the line D B from D on, be considered, it will be fulfilled when T d S in proceeding from D toward B, changes its sign. But that means: In a point lying between D and B the adiabatic passing through this point touches the line D B. If we consider the net of adiabatics, S = const., drawn on the figure, then the adiabatics at B (above J) will be steeper and at D (below J) be flatter than the slant of the line D B. The inclination of the adia-

batics is expressed (41) by $\varphi = -\left(\frac{dp_2}{dv_2}\right)_{ad}$. That of the line D B by $\tan\alpha = \frac{p_2 - p_1}{v_1 - v_2}$. Our result may therefore be expressed as

$$\left.\begin{array}{l}\text{Above J (on J, B)}, \quad \varphi > \tan\alpha \\ \text{Below J (on J, B)}, \quad \varphi < \tan\alpha\end{array}\right\} \qquad (45)$$

With the help of this relationship, we obtain at once a valuable criterion for the stability of the detonation wave. The density of the reaction products $\frac{1}{v_2}$, is greater at the wave front than the density $\frac{1}{v_1}$, of the initial explosive components at this point. A little later, i.e., behind the wave front, the combustion products will expand since the pressure, due to heat losses must sink below p_2. There is thus formed immediately behind the wave front a rarefied region whose tendency must be opposed to the progress of the compression wave. Whenever the wave front is affected by the conditions just stated it will not maintain its pressure p_2 and as a consequence, its rate of propagation will be reduced. The detonation wave will only maintain its velocity characteristic of the explosive substance as long as the velocity of this rarefied region in the reaction products and the normal velocity of the detonation wave are the same.

The velocity of the detonation wave is given by the expression $D = v_1\sqrt{\tan\alpha}$. The velocity of the rarefied area behind the wave front may be conceived of as an additive quantity made up of the velocity of sound in the reaction product

$v_2 \sqrt{-\left(\frac{dp_2}{dv_2}\right)_{ad}}$ and the mass velocity of the reaction products $W = (v_1 - v_2) \sqrt{\tan \alpha}$. The detonation wave is therefore instable as long as

$$v_2 \sqrt{\varphi} + (v_1 - v_2) \sqrt{\tan \alpha} - v_1 \sqrt{\tan \alpha} > 0,$$

that is, as long as

$$\varphi > \tan \alpha .$$

We saw from equation (45) that for those points B of the H-curve above J, φ is greater than $\tan \alpha$; and concluded therefrom that no detonation represented by such points could be stable. They will be continually weakened by the effect of the expansion of the reaction products (from cooling) behind the wave front. Any such designated point on the H-curve will slip back until it reaches J, and at this point the detonation wave will become stable; for at J, $\varphi = \sqrt{\tan \alpha}$. At this point, too, the mass velocity of the reaction products have the same velocity as the detonation wave. The detonation wave will from this point on propagate itself within the gases at a constant velocity corresponding to the point J. What are the conditions represented by the lower part of the H-curve? It seems that here for any given detonation velocity $v_1 \sqrt{\tan \alpha}$, the velocity of movements of the reaction products will adjust itself to the condition at D or B. A reference to equations (15c) and (44a) shows that D and B stand in the same relation to each other as the gas conditions in front of and behind the impulse wave, viz., that the entropy is always greater for B than it

is for D. When it is recalled that the reaction products at the moment of their formation represent the condition of maximum probability in the sense of statistical mechanics for the given order of the reaction, it would be reasonable to conclude that they would favor the condition indicated by B, and that for this reason the lower part of the detonation region of the H-curve represents no real condition. By this line of reasoning, we come to the following conclusions.

On the basis of thermodynamic probability, only detonation waves of the B-type above J in the coordinate figure, are possible. Mechanically, these waves are instable and pass over at once to the normal detonation condition indicated at J.

The point J according to the above considerations is determined by the relation

$$\frac{p_2 - p_1}{v_1 - v_2} = - \left(\frac{dp_2}{dv_2}\right)_{ad} . \qquad (46)$$

This equation gives with the general equation (40) a specific solution and definite value for normal detonation velocity.*

According to the above consideration it would indeed be possible (as by intense initial ignition) to induce detonation waves of greater velocity than normal. They would, however, soon sink to the normal rate and there remain constant. This is

*Equation (46) was first given for the case of gases by Chapman, Phil. Mag. 47, 90 (1899) but on the erroneous assumption that the entropy along the H-curve must have its maximum at the point J of normal detonation while in reality it has there a minimum. Later the equation was again developed by Jouguet, Journ. d. Math. 1 and 2, (1905) (1906).

exactly the behavior which Klast (l.c.) observed and measured with a number of explosives. This paragraph dealing with entropy offers the opportunity to call attention to the annexed coordinate figure (Fig. 9) in which the abscissas again represent specific volumes and the ordinates represent entropy. v_2 and v'_2 are the volumes corresponding to normal detonation and to maximum burning velocity. v_1 is the volume of the given explosive material. The line v_1 - G corresponds to the increase of entropy due to the chemical reaction when the same suffers no volume change nor heat loss to the surroundings. v_2 J and v'_2 K represent the entropy change due to detonation and to burning. When v_1 G is relatively small, it is possible for v_2 J to become negative, which would mean that although thermodynamically detonation is not possible, burning can still take place.

In case no chemical transformation accompanies the impact wave, the wave "degenerates" ("entartet") to an ordinary sound wave, in which case the points J, G, K, v_2, v'_2 fall together with v_1. The curve given thus represents the course of entropy change. It has at v_1 a turning point in which it coincides with the v-axis. The figure shows plainly the fact that compressional waves are identified with increase of entropy. Rarefaction waves, on the other hand, are linked with entropy decrease and are hence not realizable.

It is also to be observed that all of these conclusions drawn from the above considerations (and fulfilled by normal sub-

stances) that the magnitudes

$$-\left(\frac{d^2p}{dv^2}\right)_{ad} = \left(\frac{d\varphi}{dv_2}\right)_{ad}$$

are, in the region considered, negative; that is, accompanied by decrease of steepness and increase of volume. Since by unlimited adiabatic increase of density the pressure of every substance must increase beyond limit - which is only possible if $\left(\frac{d^2p}{dv^2}\right)_{ad}$ becomes negative - it can be said that the validity of the conclusions drawn demand that the adiabatics in the p, v-graph show no turning point. If we are to take into account also such possible abnormal substances in which a turning point does occur then the above conclusion must be expressed: In any given medium compression impulses or rarefaction impulses alone are thermodynamically possible according as the magnitude $\left(\frac{d^2p}{dv^2}\right)_{ad}$ is positive or negative.

Exactly the same conditions were met with in Section 2 (N.A.C.A. Technical Memorandum No. 505 - Part I of this article) in analyzing the mechanical possibility of the formation of compressional impulses. The quite independent criteria for the mechanical formation of compressional impulses and their thermodynamic possibility therefore rest on the same ground.

The numerical determination of the normal detonation velocity of an explosive is, in principle, completely given by (40) and (46) as soon as its chemical transformation and heat of reaction are known. The course of the calculation differs according

as we are to consider a gaseous or a solid explosive. In the case of gases the equation of state for an ideal gas may be applied to the reaction products. In the case of solid explosives this may not be justifiable.

I. Detonating Gases. If we represent by $\overline{c_2}$ the average specific heat of the reaction products at constant volume between $T_1{}^{\circ}$ and $T_2{}^{\circ}$ abs., γ_2 the ratio $\frac{c_p}{c_v}$ of the specific heats of the reaction products at $T_2{}^{\circ}$ abs., Q the heat of combustion of the chemical transformation due to detonation in ergs/gram, then in order to calculate the rate of detonation, we have the four equations

$$p_2 \, v_2 = r_2 \, T_2 , \tag{47a}$$

$$c_2 \, (T_2 - T_1) = Q + \tfrac{1}{2} \, (p_1 + p_2) \, (v_1 - v_2) \tag{47b}$$

$$\gamma_2 \, \frac{p_2}{v_2} = \frac{p_2 - p_1}{v_1 - v_2}, \tag{47c}$$

$$D^2 = v_1{}^2 \, \frac{p_2 - p_1}{v_1 - v_2} \tag{47d}$$

In these equations the magnitudes p_1, v_1, T_1, of the original components, the heat of reaction, Q and the gas constant r_2 of the reaction products, are taken as known quantities. Besides these the quantities $\overline{c_2}$ and γ_2 are known functions of T_2. This leaves the four magnitudes v_2, p_2, T_2 and D, to be determined. By making use of the equation of state of the

initial gaseous components,

$$p_1 \; v_1 = r_1 \; T_1$$

and the abbreviations

$$\mu = \frac{v_1}{v_2}$$

representing the compression in the detonation wave we obtain the following convenient expressions for carrying out the calculation

$$\overline{c_2} \; (T_2 - T_1) = Q + \tfrac{1}{2} \; (\mu - 1) \left(r_2 \; T_2 + \frac{r_1 \; T_1}{\mu} \right) \qquad (48a)$$

$$\gamma_2 \; \mu^2 - \mu \; (\gamma_2 + 1) + \frac{r_1 \; T_1}{r_2 \; T_2} \qquad (48b)$$

$$D^2 = \mu^2 \; \gamma_2 \; r_2 \; T_2 . \qquad (48c)$$

If $\overline{c_2}$ and γ_2 be given as linear functions of T_2, then from (48b) an approximate value for $\mu = \frac{\gamma_2 + 1}{\gamma_2}$ and then from (48a) a better approximate value for T_2. If a correct solution of equations (48a) and (48b) in the sense stated above has been carried out and the values of μ and T found, then (48c) gives at once the value of the detonation velocity D.

(Translator's note.- The calculation of the desired magnitudes mentioned above may be carried out with precision. The same magnitudes are also required for the calculation of specific heats of gases at high temperature where explosion methods are used. References to these methods and to theory may be found in Nernst, Theoret. Chem. 10th edition, Macmillan, p. 783 (1923). A more extended discussion with experimental results is given by Shilling, Trans. Faraday Soc. 22, 377 (1926).)

II. Solid and Liquid Explosives. If a certain degree of uncertainty enters into the calculations of the detonation velocity in the case of gases, that uncertainty becomes markedly greater when we turn our consideration to solid or liquid explosives. Since every detonation is connected with an increase of density of the reaction products, we shall have to do in this case with highly heated reaction products of a density approaching that of solids. For such cases, not only is the question of specific heats one of the greatest uncertainty, the condition of chemical equilibrium becomes very uncertain also. Further, we have no knowledge of an equation of state to fit such conditions. Detonation pressures must rise at least above 10,000 atmospheres. They are surely far greater than we are at present able to produce by mechanical means for experimental purposes of observation and measurement. Every attempt to calculate the detonation velocity of solid explosives requires assumptions concerning regions and conditions of which we are wholly ignorant. We may tentatively proceed only in this way: We may accept observations made under the highest possible pressures available and by extrapolation calculate the characteristics for detonation pressures and with these values follow through the theory developed for the determination of detonation velocities. A comparison, then, with velocities that have been observed, may give some indication of the correctness of such an extrapolation. Such a method will at least have this to recom-

mend it: It offers a possibility of gaining some insight into equations of state, specific heats and chemical equilibriums for pressures so great that we could not hope to investigate them in any other way.

As a first step in this direction, I made use of Amagat's isothermal measurements which reach to a pressure of 3000 atmospheres. From these investigations I have deduced a simple formula suitable for extrapolation for the gas nitrogen. This procedure (Z. f. Physik 4, 393 (1921)) resulted in the equation

$$p\,v = R\,T\left(1 + \frac{k}{v}\,e^{k/v}\right) - \frac{a}{v} + \frac{b}{v^{\beta+1}}\,.$$

By the use of this equation the detonation velocity of nitroglycerine and mercury fulminate were determined with an accuracy indicating the order at least of the magnitude observed. In judging of this rough agreement, the fact must not be overlooked that its uncertainty does not lie altogether in the proposed equation of state. For instance, it was assumed in this calculation that the chemical composition of the reaction products at the instant of detonation was the same as those observed after the reaction. At detonation pressures that may reach the order of 100,000 atmospheres, the reaction products may be quite different from those existing under normal conditions. The ordinary detonation of hydrogen and oxygen gas provides a good example for the investigation of these relations (Pier, l.c.). To this uncertainty respecting the chemical equilibrium, is to

be added the uncertainty concerning specific heat values for the unusual conditions met with in detonation. Indeed, in any consideration involving the condition of matter within the detonation wave it should be clearly borne in mind that any real knowledge of this region has scarcely passed the stage of a first rough guess.

10. The processes within the detonation wave.- The investigation of the processes occurring within a wave of compression (Sections 6 and 7 - N.A.C.A. Technical Memorandum No. 505, Part I) are of particular interest in reference to detonation. Since the discovery of the detonation wave by Berthelot in 1883, the question has been often and insistently discussed as to how the particles of the explosive components at the wave front are in reality brought to their extremely rapid transformation. This question lies at the very basis of any investigation of the explosive process. Detonation, at least of solid explosives, is, in fact, wholly incomprehensible as long as it is assumed that the only incitation to reaction that a single particle of the explosive receives derives from the adiabatic compression of the detonation wave. By such a compression a solid body at the temperature of liquid air, where detonation proceeds very uniformly, would be so little heated that its dissociation could not thereby be explained. The same difficulty presents itself also in the case of gases. Le Chatelier (C. R. 130, 1755 (1910)) was of opinion that an explanation could be found by assuming

that the particles in the wave front were brought by compression alone to their ignition temperature and that then the rapid chemical transformation followed. When this assumption is carried out quantitatively (van't Hoff, Vorles. u Theoret. u. physik. chem. 2d Aufl. p.245 (1901) Nernst, Theor. Chem. 8 bis 10 Aufl. 769 (1921)) for the case of carbon monoxide and oxygen, a detonation pressure of 250 atmospheres would be required; while carried out rigidly by thermodynamic theory whose correctness is substantiated by the values indicated above for detonation velocity. A pressure of only 17.2 atmospheres would be produced. Similar relationships hold for all other gaseous mixtures. The theory developed by le Chatelier is, therefore, inadequate to explain the real processes occurring within the detonation wave.

On the other hand, the conception seems reasonable that the explosive transformation of the substance depends upon a preliminary heating of its particles. In the first paragraph of this paper (Technical Memorandum No. 505, Part I), the insight afforded us concerning the processes taking place within a simple impulse wave allow us to state that this heating process depends upon heat transfer and the corresponding increase in the number of molecular impacts. We were able to show in that place that in the case of the simple sound wave that heat conduction could not be ignored but that on the contrary it played a determining role in the mechanism of the process. From the close relation

between impulse and detonation waves there can be little doubt that these characteristics apply also to the detonation wave. It seems necessary, therefore, to conclude that in the case of detonation the heating of the particles that have reached the wave front, to their ignition temperature, takes place principally through heat conduction from the particles last burned (that is, by the impacts of individual molecules from the very thin wave of high temperature).

It is interesting to observe that the most successful experimenters in the field of gas detonation, Berthelot and Dixon, also made use of such an assumption. They conceived that from the hot wave front molecules were thrown forward that shared their high kinetic energy by impact with the molecules in front of the wave and thereby brought them to a condition of activation. This conception seems more reasonable than the one offered by le Chatelier. (The photographic records upon which le Chatelier based his "dark compressional waves" to prove his theory, were later shown by Dixon (l.c. 1903) to be contrast effects of the plate and not admissible as evidence.) Berthelot and Dixon, however, were both in error in so far as they sought to justify their theory from the observed values of detonation velocity. They did not know that these values (expressed in the thermodynamic equations (40), (46)) were independent of the microscopic processes, whatever they might be, taking place within the wave front, and that the same values were arrived at by the applica-

tion of classical dynamics.

In conclusion I wish to state emphatically that the discussion in this last paragraph is confined solely to the question of the wave's propagation after once being started. The problem of the origin of the detonation wave or the inception of an explosion is not here considered.

Summary of Results

When proper consideration is paid to friction and heat conduction that must be present with all bodies, it is shown in the analysis made of compression impulses that the theory of instable surfaces may be dispensed with.

The actual thickness of the wave front has been numerically determined for a gas and for a liquid.

By the introduction of a chemical transformation within the impact wave a complete general conception of detonation and normal burning is secured.

While the complete analysis and calculation of the rate of normal burning has not yet been effected, the present consideration, by making use of the principle of stability, has been able to set a definite value for normal detonation velocity. This value is in excellent agreement with observed results in the case of gases and gives fair approximations for the case of solids.

By application of the deductions here presented, the possibility is offered of following the physical characteristics and chemical transformations experimentally to an order of 100,000 atmospheres pressure.

An important difficulty in understanding detonation phenomena is overcome by a consideration of heat conductivity.

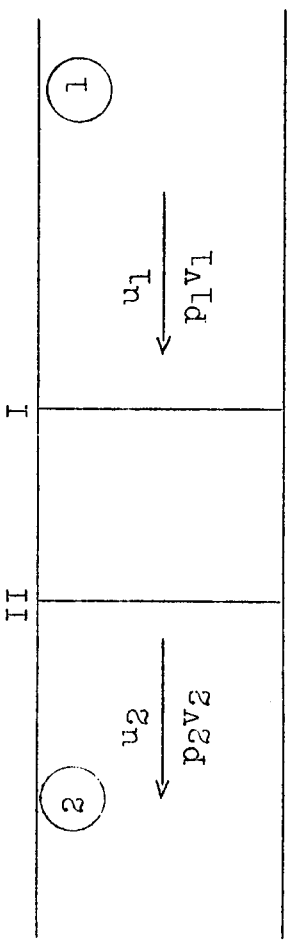

Fig.7

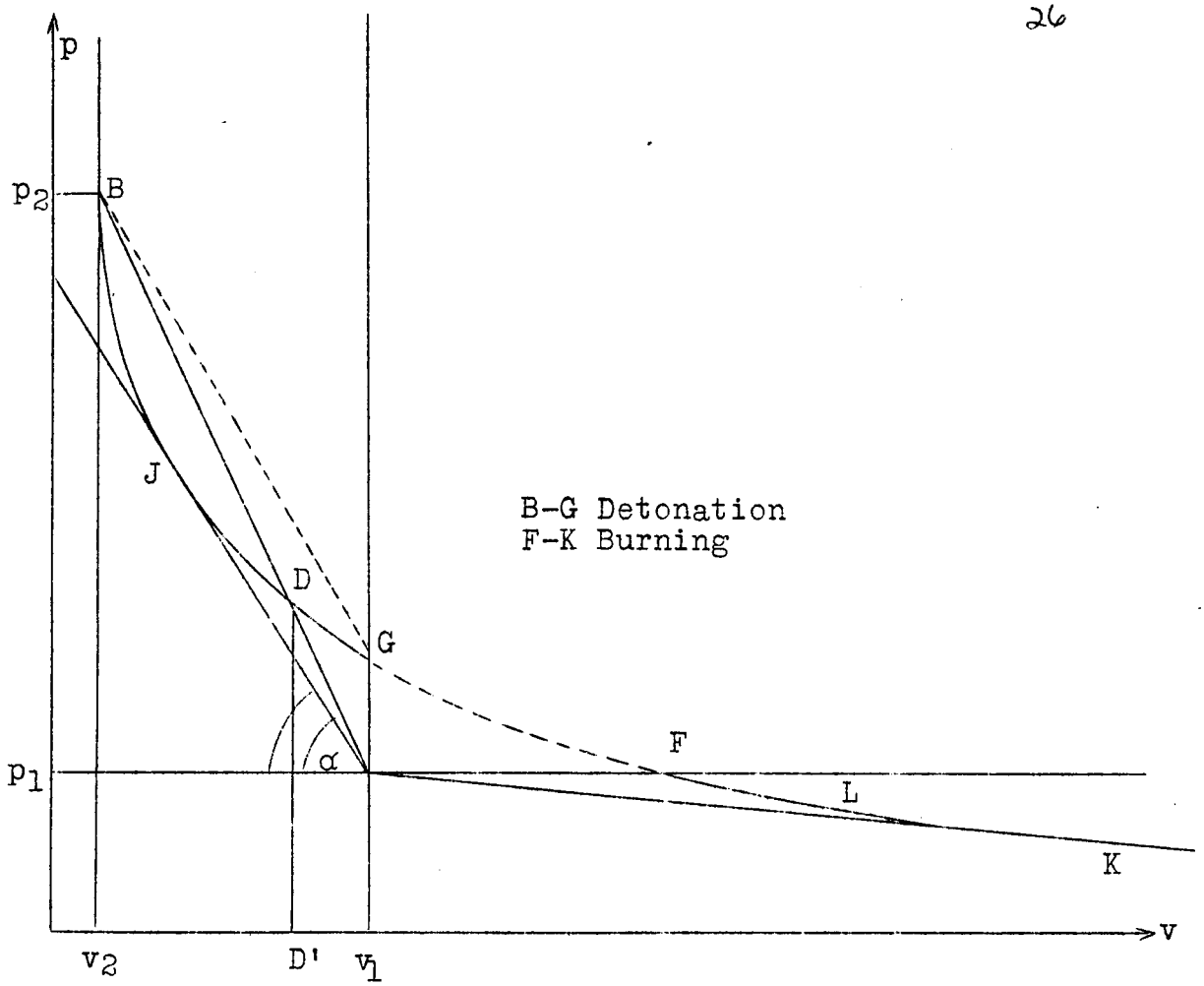
p
p_2
B
J
D
G
F
p_1
α
L
K
v
v_2
D'
v_1
B-G Detonation
F-K Burning

Fig.8

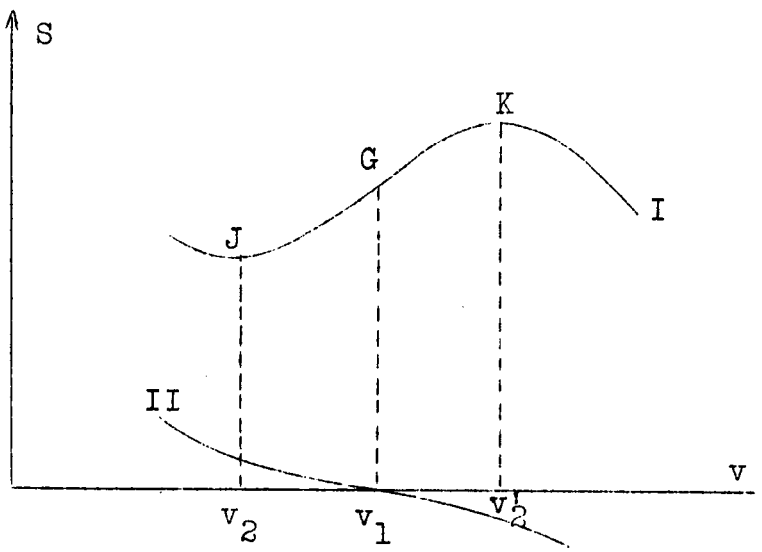
S
K
G
I
J
II
v
v_2
v_1
v_2'

Fig.9